

# Demonstration of nm-level Active Metrology for Long Range Interferometric Displacement Measurements

Muthu Jeganathan and Serge Dubovitsky  
Jet Propulsion Laboratory,  
California Institute of Technology,  
4800 Oak Grove Dr., Pasadena, CA 91109

## ABSTRACT

We report on the laboratory demonstration of an active linear metrology scheme using two separate lasers. In “active” metrology, the passive retroreflector in one arm of the interferometer is replaced with an active optical transponder. The Transponder can dramatically boost the returned signal strength, thereby providing a way to perform metrology and pathlength control over long ( $> \text{km}$ ) distances. Two Lightwave Electronics non-planar ring oscillator (NPRO) lasers at a wavelength of  $1.319 \mu\text{m}$  were used as the Source and Transponder. The frequency of the Transponder is offset locked to the signal received from the Source using the Lightwave Laser Offset Locking Accessory (LOLA), and the Transponder beam is sent back to the Source. The phases of the beat signals are measured locally at the Source and Transponder by appropriately demodulating the signal, and post-processed to determine displacement. In initial experiments, the standard deviation of the measurement errors was less than three nanometers.

**Keywords:** Active Metrology, Two-laser metrology, heterodyne interferometer, ST3, TPF, LISA

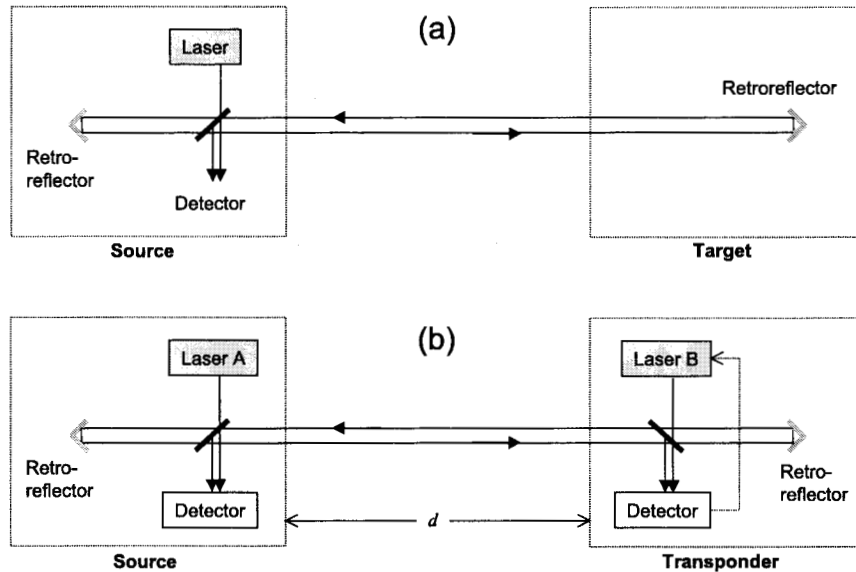
## 1. INTRODUCTION

Optical interferometry is a well established technology for implementation of high-resolution displacement metrology systems. A number of interferometer configurations, Michelson heterodyne probably being the most common, are currently used for sub-micron displacement measurements in a variety of applications involving a wide range of target distances. Commercial optical interferometers are available for displacement measurements over relatively short target distances (less than tens of meters) with better than 1-nm resolution. Presently the use of interferometers is being extended to applications requiring nanometer or sub-nanometer resolution over target distances from hundreds of meters to millions of kilometers. For example, ground- and space-based stellar interferometers, such as Navy Prototype Optical Interferometer (NPOI)<sup>1</sup> and Space Technology 3 (ST3)<sup>2</sup> mission, require nm-level pathlength stabilization over hundreds of meters. EX5 (any refs?), a follow-on to the Gravity Recovery and Climate Experiment (GRACE)<sup>3</sup> mission, requires accurate range knowledge over 100 km. Gravity wave detection experiments such as Laser Interferometer Space Antenna (LISA)<sup>4</sup> missions require pathlength stabilization over even longer distances.

High-resolution interferometric measurement across a long target range presents a considerable challenge in getting enough optical power back from a passive target to obtain the required high signal-to-noise ratio. In a typical interferometer, where a metrology beam is reflected by a retroreflector placed on a target (Fig. 1a), the diffraction losses scale as  $d^8/(\lambda^4 L^4)$ , where  $L$  is the target range,  $d$  is the acceptance aperture of the reflector and receiver, and  $\lambda$  is the wavelength. As a result of the  $L^4$  dependence, source-target distances quickly become limited by the available metrology power. For example, in ST3, a separated spacecraft stellar interferometry mission to be launched in 2005 by NASA, the two spacecraft are separated by as much as 1 km and the effective optical pathlength between them must be monitored to 5 nanometers. Practical considerations limit the metrology beam size and target aperture to 2 centimeters resulting in less than 1% of

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Please direct all correspondence to Muthu Jeganathan - email: muthu.jeganathan@jpl.nasa.gov, Tel: (818) 354-9400, Fax: (818) 393-614



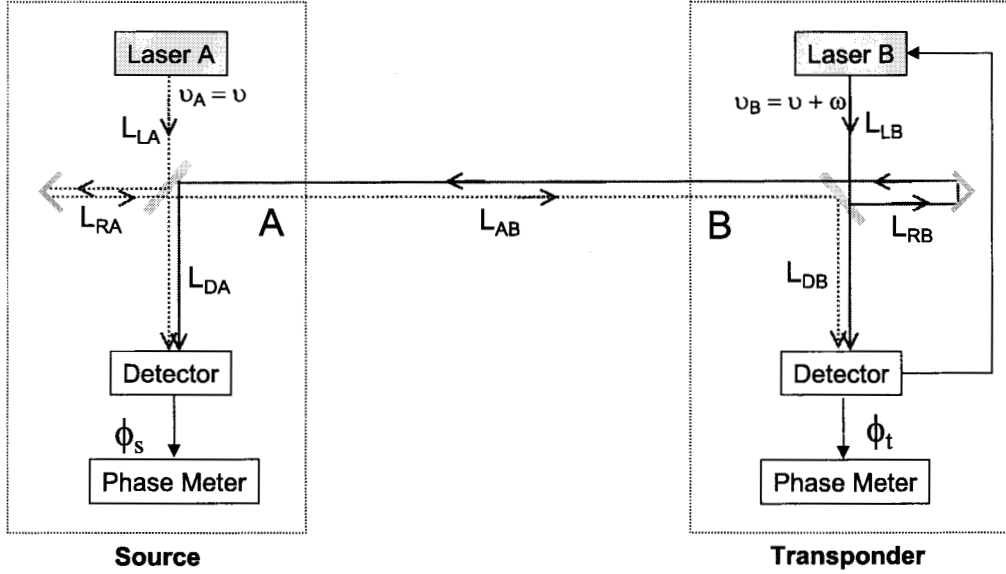
**Figure 1.** a) A typical heterodyne interferometer with a passive retroreflector as the target. b) Active metrology with phase detector and laser as the Transponder. Source remains essentially the same in both cases.

optical power at the detector. With approximately 100 mW of optical laser power, ST3 metrology is doable with a passive retroreflector. Active metrology may be suitable for missions like EX5 with a range of 100 km. Further enhancements will be required for missions such as LISA where spacecrafts will be separated by millions of kilometers.

One can extend the range of interferometric metrology by providing optical gain at the target to make-up for some of the diffraction losses. Use of an optical amplifier to boost the signal received at the target, and actively pointing the beam back at the source is one option. Amplified Spontaneous Emission (ASE) and phase noise introduced by the medium may limit its usefulness. Another possibility is to use a phase conjugate mirror (PCM) with gain. Efficiency and signal threshold consideration may make PCMs impractical in space. Yet another option is the concept of active metrology proposed by Shao,<sup>5</sup> where the passive retroreflector is replaced with an active optical transponder (as in Fig. 1b).

In active metrology, the target detects the phase of an incoming metrology beam and sends back a locally generated laser beam whose phase is referenced to the phase of the incoming beam. For convenience, we will call the side with the free-running laser as the Source and the side with laser referenced to the Source as the Transponder. One must either know the phase relationship between the two beams or control it by phase locking the reflected beam to the incoming beam. For example, if the returned Transponder beam was phase locked to an incoming beam with 180 degree phase shift, the scenario would be analogous to reflection by a mirror. Though active metrology requires both opto-electronic conversion and active pointing, it appears to be the most practical.

Active metrology was partially demonstrated by R. Morgan *et al.*<sup>6</sup> In that experiment, a single HeNe laser was split with a fiber-optic coupler and used for both the Source and Transponder. To simulate the effect of two lasers a fixed frequency offset was introduced by an acousto-optic modulator which, of course, does not introduce any significant phase or frequency noise between the "two" lasers. The authors demonstrated a short time scale resolution of approximately 20 nanometer. In this paper, we build on Morgan's work and demonstrate a true two-laser, active, linear metrology with a displacement measurement resolution of <3 nanometers.



**Figure 2.** Figure showing the various pathlengths in active metrology. All components in the Source have a subscript A while those in the Transponder have a subscript B.

In our implementation of active metrology, we offset lock the frequency of the laser on the Transponder to that of the laser on the Source using commercially available components. The frequency offset between the lasers produce a heterodyne beat at the Source and Transponder whose phase is measured with respect to a local oscillator (LO). Our implementation has several advantages: a) the Transponder is nearly identical to the Source, significantly reducing R&D costs; b) it eliminates self interference (aka polarization leakage) problems; and b) eliminates the need for frequency shifters or phase modulators and consequently reducing system losses.

Below, we briefly present a theory that relates the measured phases to changes in optical path length. It is followed by a section on the performance of the Transponder. That is, the capability of offset locking of one laser to another. We finally describe the active metrology optical and electronics setup, and results obtained from them.

## 2. THEORY

Fig. 2 shows a simplified schematic of the active metrology scheme identifying the various pathlengths involved. Note the similarity between the Source and the Transponder in Fig. 2. The only difference being the laser in the Transponder is offset locked to the Source laser. Because of the frequency offset, the detectors on the Source and the Transponder see a beat note at the offset frequency. Phase meters are used to measure the phases of the beat notes with respect to local oscillators. Changes in any of the optical pathlengths result in a phase change at either one or both detectors.

The objective of the metrology system is to measure changes in pathlength between two reference corner-cubes, i.e. changes in distance  $d = L_{RA} + L_{AB} + L_{RB}$ . Active metrology will be used only in situations where the Source-Transponder distance is much larger than any of the internal distances, i.e.  $L_{AB} \gg L_{LA}, L_{RA}, L_{DA}, L_{LB}, L_{RB}, L_{DB}$ . So there is a one-way time delay of approximately  $\tau = L_{AB}/c$  seconds between the Source and the Transponder. Though this condition is not satisfied in the lab, we will use it in the analysis below as it better describes the intended configuration.

Given that a pathlength  $L$  results in a phase delay of  $2\pi L/\lambda = 2\pi\nu L/c$ , One can show that the phase

measured at the Source at some time  $t$  is:

$$\begin{aligned}\Phi_s(t) = & \phi_{0s}(t) + \frac{2\pi}{c}(L_{LA} + L_{DA})\nu_A(t) \\ & - \left[ \phi_{0t}(t - \tau) + \frac{2\pi}{c}(L_{LB} + 2L_{RB} + L_{AB} + L_{DA})\nu_B(t - \tau) \right]\end{aligned}\quad (1)$$

where  $\lambda$  is the wavelength of light  $\phi_{0s}$  is the initial phase of the Source laser;  $\nu_A$  and  $\nu_B$  are the frequencies of the Source and Transponder laser beams, respectively; and  $c$  is the speed of light in vacuum. Similarly the phase observed at the Transponder is:

$$\begin{aligned}\Phi_t(t) = & \phi_{0t}(t) + \frac{2\pi}{c}(L_{LB} + L_{DB})\nu_B(t) \\ & - \left[ \phi_{0s}(t - \tau) + \frac{2\pi}{c}(L_{LA} + 2L_{RA} + L_{AB} + L_{DB})\nu_A(t - \tau) \right]\end{aligned}\quad (2)$$

The difference between these phases measured at the Source and Transponder provides a measure of the pathlength and can be written as:

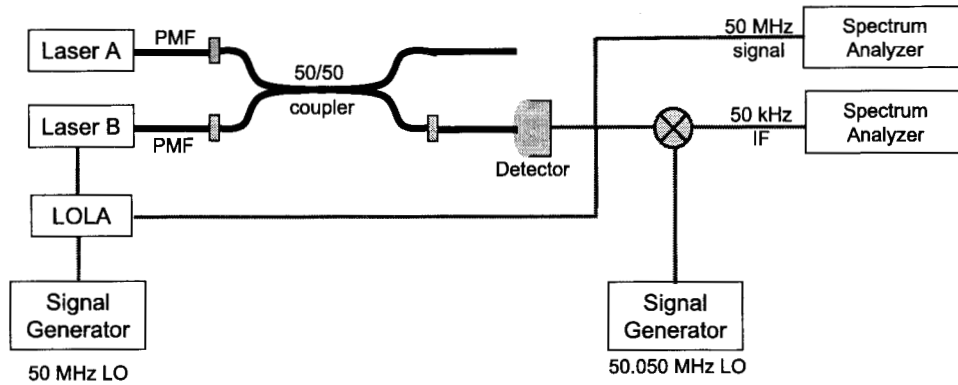
$$\begin{aligned}\Delta\Phi(t) = \Phi_s(t) - \Phi_t(t) = & \frac{2\pi}{c} 2(L_{RA} + L_{AB} + L_{RB}) \nu_A(t - \tau) \\ & + \Delta\phi_{0s}(\tau) + \Delta\phi_{0t}(\tau) \\ & + \frac{2\pi}{c} (L_{LA} + L_{DB}) \Delta\nu_A(\tau) \\ & + \frac{2\pi}{c} (L_{LB} + L_{DA}) \Delta\nu_B(\tau) \\ & + \frac{2\pi}{c} (L_{DA} - L_{DB}) f(t) \\ & + \frac{2\pi}{c} (L_{AB} + 2L_{RB}) f(t - \tau)\end{aligned}\quad (3)$$

where  $f = \nu_B - \nu_A$  is the frequency difference between the two lasers; and  $\Delta\phi_0(\tau)$  and  $\Delta\nu(\tau)$  are the laser phase and frequency change over time  $\tau$ . The first term in the above equation is the desired signal which is proportional to the round trip light path. Since  $L_{AB}$  is much larger than the internal distances and  $\nu \gg f$ , the first term dominates. The resolution of the measurement is the variance of Eq. 3. If the lengths are fixed, the frequency and phase stability of the lasers over time determine the resolution of the system. The second term is the phase noise of the lasers and is related to the linewidth of the lasers. The third and fourth terms in Eq. 3 are related to the frequency stability of the laser and locking system. The Source laser needs to be locked to a stabilized cavity to improve performance. The stability of Laser B depends on how well the offset locking works. The last two terms with  $f$  in Eq. 3 are inherent in a heterodyne system and could be eliminated if the frequency offset between the two lasers is zero. Note that by making phase measurements with different offset frequencies, one can increase the ambiguity range (analogous to two-color absolute metrology).

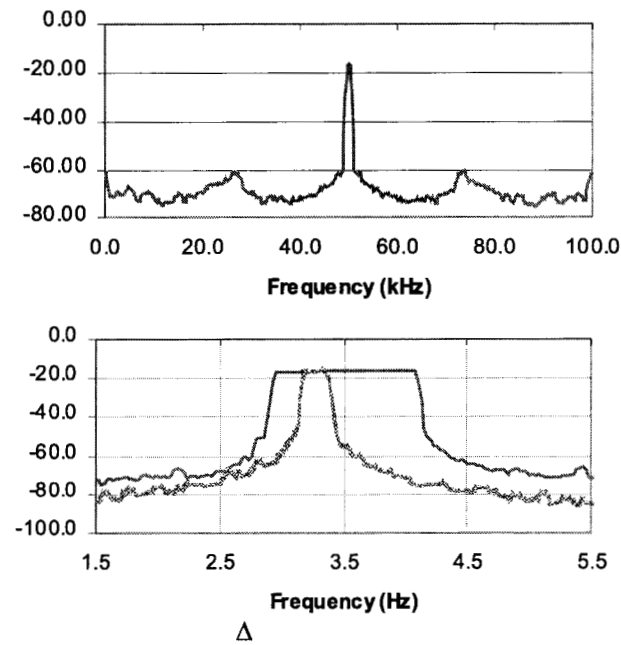
### 3. EXPERIMENTAL SETUP AND RESULTS

#### 3.1. Offset Locking of Lasers (OLL)

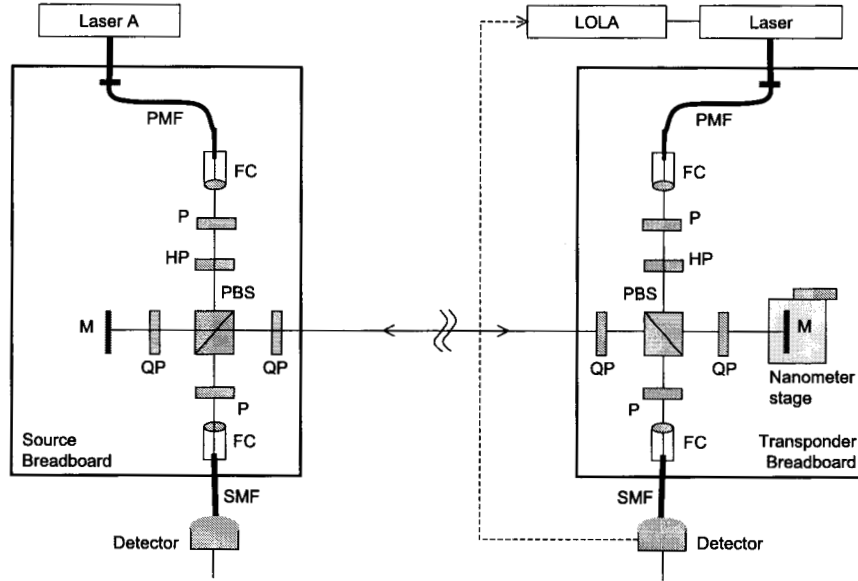
One of the essential requirement to demonstrate active metrology is the ability to lock the frequency of one laser to that of another with a known offset. We accomplished this with two 1.319  $\mu\text{m}$  non-planar ring oscillator (NPRO) lasers (Model 125) and a Laser Offset Locking Accessory or LOLA (Model 2000), all from Lightwave Electronics (Mountain View, California, USA). The fiber-coupled lasers can put out up to 100 mW of CW power and have a linewidth specification of less than 5 kHz. The setup to measure how well the LOLA works is shown in Fig. 3. One of the lasers, Laser A, is uncontrolled and independent. In practice, however, this laser will be controlled by a stable cavity. The other laser, Laser B, is controlled by the LOLA. The output from both lasers are mixed using a 50/50 PM fiber coupler and the attenuated signal from the coupler is detected on a InGaAs detector/amplifier unit with 125 MHz bandwidth (Model 1811 from New Focus). The RF signal from the detector is fed to the LOLA and monitored on a spectrum analyzer. The LOLA controls the crystal temperature and piezo-electric element in laser B so that the beat signal from the



**Figure 3.** Block diagram of experimental setup to characterize offset locking of lasers with Lightwave's LOLA.



**Figure 4.** a) Spectrum of the beat frequency after down-conversion to 50 kHz. b) Same spectrum zoomed in near the center frequency. The gray line shows the spectrum for short (few minutes) duration while the solid line shows the spectrum over 12 hours.



**Figure 5.** Optical setup for active metrology demonstration. In lab, the fixed mirror on the Source and QI mirror on the Transponder were separated by approximately 60 cm. Abbreviations in the figure are: PMF - polarization maintaining fiber; FC - fiber collimator; P - polarizer; HP - half-wave plate; QP - quarter-wave plate; PBS - polarizing beam splitter; M - mirror; and SMF - single mode fiber.

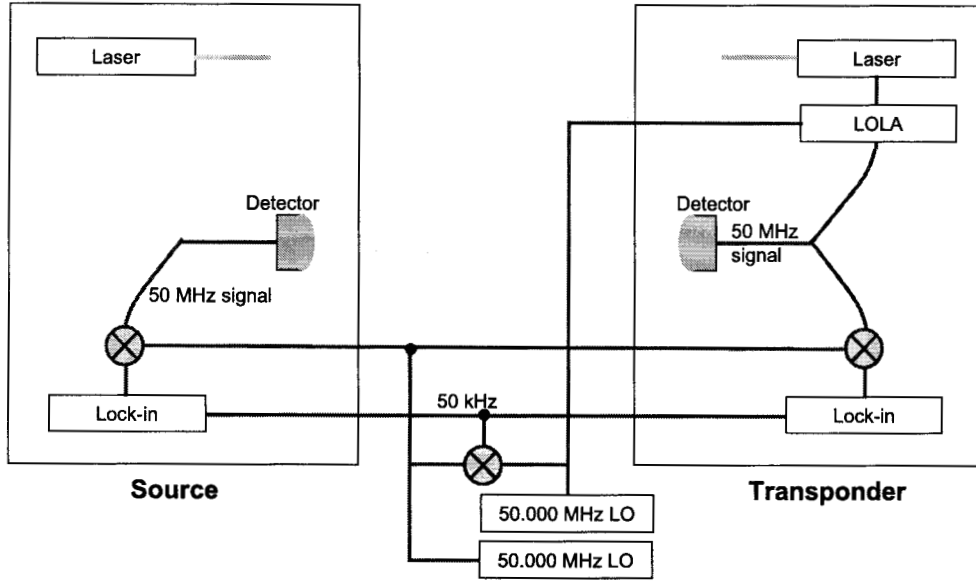
detector matches the reference signal from a function generator. The LOLA can offset lock two lasers with a frequency offset of 10 MHz to 1 GHz. We chose to perform all our experiments at 50 MHz.

A spectrum of the beat between the two lasers is shown in Fig. 4a. Here the photo-diode output at 50 MHz is down-converted to 50 kHz using a mixer and second frequency generator. One can see from Fig. 4b that the spectral width of the beat frequency over several minutes is less than 0.25 Hz. With time, the beat frequency slowly drifts. We measured the drift to be approximately 2 Hz over 12 hours with an external HP 8648A function generator. When we used the internal generator in the LOLA, the drift was much larger (>15 Hz). We have not isolated the source of the drift but it is most likely due to drift of the function generator outputs. With offset locking working well, we proceeded to demonstrate active metrology as discussed earlier.

### 3.2. Active Metrology

Active metrology was demonstrated in lab using the experimental configuration shown in Fig. 5. Light from the polarization-maintaining (PM) single-mode-fiber (SMF) of Laser A is incident on a polarizing beam-splitter (PBS) through a polarizer and half-wave-plate (HWP). The set of polarizer, HWP and PBS together allow variable attenuation as well as variable split-ratio. The input to the PBS is polarized such that most of the light (s-pol) is reflected while a small fraction (p-pol) is transmitted. The reflected wave passes through a quarter wave plate (QWP), bounces off a mirror and goes back through the same QWP. Note that we have used reference mirrors instead of the usual corner-cubes for convenience. The double-pass through the QWP converts the s-pol light to p-pol which is subsequently transmitted through the PBS to the target or Transponder. In an identical manner, significant fraction of the light from Laser B reaches the Source. The two QWPs in between the two PBS rotate the p-pol light to s-pol light which is reflected by the PBS to the detector. This wave (s-pol) from Laser B and the transmitted wave (p-pol) from Laser A are combined and coupled into a SMF and detected. The polarizer PA2, at the proper angle, ensures that the two orthogonally polarized light interfere. The interfered light has a beat note at the offset frequency of 50 MHz. The phase of the 50 MHz signal is then measured with respect to a local oscillator.

In a very similar fashion, the detector on the Transponder sees the beat signal between p-pol light from

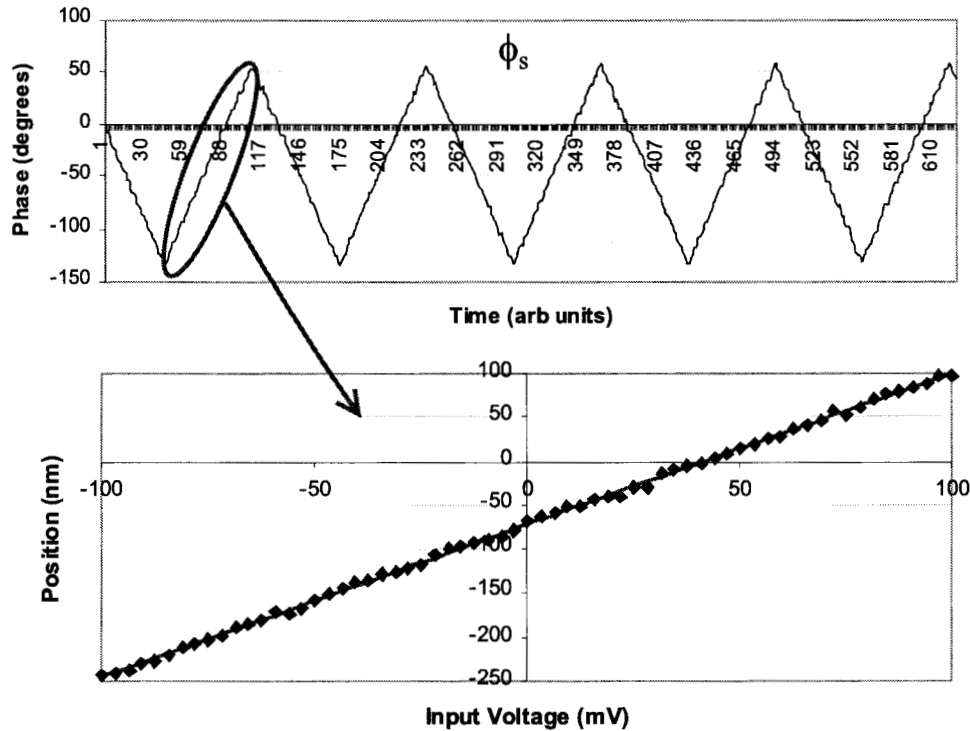


**Figure 6.** Block diagram of electronics arrangement for active metrology demonstration.

Laser B and s-pol light from the Source. Moreover, the beat signal from the detector is fed into the LOLA to control frequency of Laser B. In the experimental setup, the only other difference between the Source and the Transponder is that the reference mirror in the Transponder is mounted on a piezo-electric stage to verify the accuracy of the interferometer. We used a single axis nano-positioning-stage (model NPS-Z15B) with DSP-based controller (model NPS3110-ANA) from Queensgate Inc. (QI) to move the mirror along the optical axis by a fraction of a wavelength. The QI stage has a resolution of  $< 1$  nm. The mirror motion thus results in a path length change between the two reference mirrors which can be readily measured by the interferometer.

As noted earlier, the frequency shift between Laser A and Laser B results in a 50 MHz signal at the output of the detectors. To determine pathlength changes, the phases of these beat signal with respect to a local oscillator needs to be measured. Since it is difficult to measure the phase at such high frequencies we use RF mixers and additional function generators to down-convert the photo-detector signal from 50 MHz to 50 kHz for measurement of phase with commercial lock-in amplifiers (Fig. 6). The phases,  $\Phi_A$  at the Source and  $\Phi_B$  at the Transponder are measured using lock-in amplifiers (Model SRS830 and SRS844) from Stanford Research Systems. Ideally, there would be separate stable local oscillators on both the Source and the Transponder. One can get rid of the mixers by operating at a much smaller heterodyne frequency or using high-frequency RF lock-in amplifiers.

To measure the resolution of our active metrology system, we applied a 1-Hz, 200 mV peak-peak, triangular wave to the analog input of the Queensgate nano-positioning stage (NPS). This input signal produced a pathlength change of approximately 350 nm. The range was kept small to avoid counting full cycles in our simple setup. Fig. 7a shows the phase,  $\Phi_A$ , measured at the Source as the QI mirror is moved back and forth. Note that because of the use of the LOLA on the Transponder, Laser B's phase is shifted to compensate for any phase changes seen by the detector on the Transponder. In our experiments,  $\Phi_B$  changed by less than 1 degree over time. This is highly desirable, especially when  $\tau$  is large, as the Source can determine changes in pathlength without information from the Transponder. Consequently, we will concentrate on  $\Phi_A$  and ignore  $\Phi_B$ . Fig. 7b zooms into a subset of what is in Fig. 7a to show a single ramp from -100 to 100 mV. Analysis of residuals (difference between measured and fit data) from the fit show the standard deviation of the measurement errors to be 2.6 nm. Ramps at slower frequency (0.2 Hz) yielded similar results. To minimize effects of air currents, the optical setup was covered with a cardboard box, without which the standard deviation was significantly higher.



**Figure 7.** a) Source phase,  $\Phi_A$  as a function of time while the QI mirror is moved back and forth. b) A subset showing a linear ramp of the QI mirror. The diamond points show the data point while the solid line is a linear fit.

#### 4. CONCLUSIONS

In summary, we have demonstrated active linear metrology, with a resolution of better than 3 nm, that can be used to measure optical path length changes over long distances. In our implementation of active metrology, we used a commercial laser and a commercial offset locking device to build a Transponder that replaces a passive retroreflector in a standard heterodyne interferometer. The active “reflection” at the Transponder makes up for some of the diffraction losses which scales as distance to the fourth power with a passive target. These results indicate the suitability of active metrology for future projects requiring long-range displacement measurements. To simulate more practical scenarios, however, we need to a) replace the common function generator with separate and stable local oscillators at both ends; and b) introduce realistic propagation delays and power losses.

Significant work still needs to be done in understanding the noise sources and practical limitations on the system resolution. The impact of long time delays and measurement integration time also need to be studied. Reliable predictions of active metrology performance with existing components will be highly beneficial in performing trade-off studies for upcoming missions.

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